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N63-15034

NASA TN D-1777

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NASA TN D-1777

TECHNICAL NOTE

D-1777

AIRCRAFT VORTEX WAKES IN RELATION TO TERMINAL OPERATIONS

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

WASHINGTON April 1963

Code-1

INTRODUCTION

In recent years there have been increasingly frequent reports by pilots of encountering very severe disturbances in the wake of another airplane, even when separated from it by distances of several miles. There are also an increasing number of fatal accidents to lighter airplanes, resulting from upsets near the ground or structural failure, which are being ascribed to encounters with the wakes of large airplanes. It is now generally accepted that the only disturbance which an airplane can produce that is powerful enough and persistent enough to account for these incidents arises from the vortices which trail from the wing tips of any airplane in flight. (See fig. 1.)

The purpose of this paper is to examine the problems associated with trailing vortices, particularly in the airport terminal area where separation of aircraft must be kept to a safe minimum for efficient traffic handling and where the low flight speeds are associated with relatively more intense vortices. A brief discussion is given of the formation of trailing vortices from lifting surfaces and of the effects of such major factors as aircraft weight, wing span, and speed on intensity and extent of the resulting airflow disturbance. The decay of vortex intensity with time is considered in the light of available experimental results and theory. Effects on aircraft encountering trailing vortices, including structural loads, upset, and settling are considered together with the influencing factors. Finally, the theoretically determined time-wise settling and spreading of the trailing vortices from an airplane in typical take-off and landing is described and discussed in relation to safe procedures for following airplanes.

Airplanes considered as examples in the discussion include a heavy jet transport of 300,000 pounds gross weight, a 35,000-pound light turboprop transport, and a 2,000-pound light personal airplane. Pertinent characteristics of these airplanes are listed in the following table:

TABLE I.- CHARACTERISTICS OF AIRPLANES CONSIDERED

	Heavy transport airplane	Light transport airplane	Light personal airplane
Weight, lb	300,000	35,000	2,000
Wing area, sq ft . . .	2,900	750	148
Span, ft	140	95	30
Aspect ratio	7	12	6

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SUMMARY

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An analysis has been made, on the basis of present understanding of trailing vortex characteristics, to provide an indication of the possible effects on aircraft encountering these vortices, the circumstances under which encounters might occur in terminal-area operations, and some means of dealing with the vortex problem in operations planning and traffic control.

Relative to the effects of vortex penetration, the smaller, lighter airplanes will generally be most severely affected by a given vortex field and, furthermore, are susceptible to the trailing vortices of the whole spectrum of larger, heavier aircraft. A light airplane penetrating at right angles to the vortex of a heavy transport in intersecting traffic patterns can be subjected to loads sufficient to cause primary structural damage. In the "follow-the-leader" situation of take-off or landing behind a larger airplane, the lightplane may be subjected to a strong downdraft between the vortices of the preceding airplane which, if too close to the ground, could cause it to settle to the ground; or, if caught near the center of one of the vortices, it could suffer a large rolling upset in spite of anything the pilot could do to correct it. Although the larger airplanes will not respond as vigorously as a lightplane to the disturbances of a vortex field, the settling or rolling effects from the vortices of the preceding airplane of equivalent or larger size and weight can be severe enough to be dangerous near the ground. This is particularly true in landing where the established rate of descent tends to increase the difficulty of recovery.

As an alternative to allowing 2 to 3 minutes for vortex dissipation in separating terminal-area traffic, procedures are suggested which, in many cases, would give reasonable assurance that vortices would not be encountered and would thereby permit shorter separation times. By insuring that a following airplane remains on or above the flight path of a preceding one, if of equal or greater size and weight, serious vortex effects could not occur even at separation times as short as 1/2 minute. This result could frequently be achieved if traffic control procedures could be developed which, in arranging the sequence of traffic, would take account of the varying runway length requirements, climbout and glide-slope capabilities, and susceptibility to vortex effects of the various aircraft involved. Visual glide-slope systems could be of substantial benefit in providing positive control of flight path for vortex avoidance in landing.

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*Presented at Symposium on the Development of Analytical Models for Estimating Airport Capacity sponsored by Institute of Transportation and Traffic Engineering, University of California, November 29-30, 1962. By arrangement with the University, the present publication is being released to provide increased availability.

SYMBOLS

A	aspect ratio
b	span of airplane, ft
$\bar{c}$	mean chord of generating airplane, ft
F	vertical load, lb
K	constant determined from experimental data
r	radial distance from vortex center, ft
S	wing area, sq ft
t	time after vortex generated, min
V	forward speed of airplane, ft/sec
w	induced tangential velocity, ft/sec
W	weight of airplane generating vortices, lb
$\dot{y}_V$	lateral velocity of vortices, ft/sec
$\dot{z}_V$	vertical velocity of vortices, ft/sec
Γ_o	circulation about vortex, ft^2/sec
ν	kinematic viscosity of air, ft^2/sec
ν_e	effective eddy viscosity, ft^2/sec
ρ	air mass density, slugs/cu ft

CHARACTERISTICS OF TRAILING VORTICES

Formation of Vortices

It has long been established both by theory and experiment (for example, ref. 1) that a finite-span lifting wing sheds, in effect, a continuous sheet of vorticity along its trailing edge, which, being unstable, rolls up quickly into a pair of vortex cores behind each wing near the tips as illustrated roughly in figure 1. The rolling-up process is essentially completed within two to four span lengths behind the airplane, for the conditions considered herein.

Within the vortex cores the air rotates about the center in the directions indicated in figure 1, similar to a rotating solid body, with zero velocity at the center and increasing to a maximum at the effective boundary of the core. Outside the cores the tangential air velocities induced by the vortices decrease as the inverse of radial distance from the vortex centers, with a downward motion between the pair of vortices and an upward motion outside the vortices.

Vortex-Induced Air Velocities

The intensity of the air disturbance created by the trailing vortices of an airplane, that is, the magnitude of the air velocities induced, is primarily a function of the weight, span, and forward speed of the airplane and the density of the air in which it is operating. The tangential velocity about the center of each vortex outside of the cores can be expressed as

$$w = \frac{2W/S}{\pi^2 A\rho V} \cdot \frac{1}{r/b} \tag{1}$$

As indicated in figure 1, the induced flow is clockwise about the vortex from the left wing tip and counterclockwise about the opposite vortex, as viewed from the rear. The relation (1) involves the assumptions, used throughout this paper, that the airplane is flying steadily and has an elliptical span-load distribution. Velocities in the vortex cores will be discussed later.

The lateral positions of the vortex centers for an airplane with elliptical span loading are initially $\frac{\pi}{4}\frac{b}{2}$ from the center line of the airplane. (See ref. 1.)

Vortex Settling and Spreading

Since each of the vortices trailing from an airplane produces a downward movement of the air at the position of the opposite vortex, the vortices settle or move downward with time. If the vortices are generated more than a few span lengths above the ground, they tend to maintain a constant lateral spacing $\frac{\pi}{4} b$ and have a constant downward velocity $\dot{z}_v$ given by the relation

$$\dot{z}_v = \frac{8W/S}{\pi^3 A\rho V} \tag{2a}$$

As the vortices approach the ground to within two or three span lengths their vertical motion is slowed and they begin to spread apart laterally. The vertical motion ceases at a height of $\frac{\pi}{4}\frac{b}{2}$ and the lateral velocity $\dot{y}_v$ of the vortices (in opposite directions) attains the same value as the initial vertical velocity or

$$\dot{y}_v = \frac{8W/S}{\pi^3 A\rho V} \tag{2b}$$

When the vortices are generated closer to the ground, their initial vertical velocity is less, they settle to a level somewhat closer to the ground, and spread laterally at a faster rate than is indicated previously. A complete theoretical treatment of vortex movement resulting from mutual interaction and the effects of ground proximity is given in reference 2.

These vortex motions are a very important aspect of the problem of avoidance of vortex encounters and will be discussed in this light at a later point.

The computed path of a pair of vortex elements generated by a heavy transport airplane flying at a speed corresponding to take-off or landing is shown in figure 2 together with the positions of the vortices at various times. For the heavy transport case shown, the rate of travel of the vortices is about 350 feet per minute. For the light transport or light personal airplane in take-off or landing, the rate would be about 150 feet per minute.

Vortex Decay

In the central region or core of a trailing vortex tangential shear forces develop which cause the core to grow with time and the core velocities to decrease.

An accepted theory is available which defines the radial distribution of velocity through the vortex as a function of time for the case where the shear forces result from viscous effects only (molecular motions). (See, for example, refs. 2 and 3.) In accordance with this theory, the velocity field of a vortex can be expressed as

$$w = \frac{\Gamma_o}{2\pi r}\left[1 - \exp\left(- \frac{r^2}{4\nu t}\right)\right] \tag{3}$$

This relation indicates a growth of the core and a diminishing of velocities that is much slower than that apparent from observations of trailing vortices.

In the actual case of the trailing vortices of an airplane, the effects of turbulence or eddying flow would be expected to be present in addition to viscous effects, and therefore much higher shear forces than those associated with viscosity would be produced and more rapid degeneration of the vortices than equation (3) would indicate. Turbulence effects in the vortices can arise from atmospheric turbulence and from the turbulent wake of the airplane, created by skin-friction drag and entrained in the vortex core in the rolling-up process. Several investigators (for example, refs. 2 and 3) have suggested that the velocity profiles of airplane trailing vortices would have the form defined by equation (3) but with an effective eddy viscosity ν_e added to the kinematic viscosity ν (or replacing it, since ν would be expected to be relatively very small). Limited experimental evidence (ref. 4) tends to support this concept of the form of the vortex velocity distribution but available experimental results are too limited to permit an adequate determination of the relations between meteorological and aircraft factors and the effective eddy viscosity.

A limited analysis suggests that in the absence of atmospheric turbulence the eddy viscosity would be given by the relation

$$\nu_e = K\bar{c}\Gamma_o \tag{4}$$

From experimental results with two widely different airplanes (refs. 3 and 4), both presumably obtained in essentially turbulence-free air, a value of K of 3×10^{-5} was obtained which appeared to fit both sets of data reasonably well. From the foregoing considerations the following relation was derived for the time variation of the velocity profile of trailing vortices in calm air:

$$w = \frac{\Gamma_o}{2\pi r}\left\{1 - \exp\left[-\frac{r^2}{\left(42b^2 + 1.2\bar{c}\Gamma_o t\right)\left(10^{-4}\right)}\right]\right\} \tag{5}$$

The left-hand term in the denominator of the exponential is included to account for the fact that the vortex develops a finite core in the rolling-up process which generally requires only a very few seconds. (See ref. 1.) This initial rollup is therefore considered to be complete at zero time. From the well-known relation

$$\Gamma_o = \frac{4W}{\pi b\rho V} \tag{6}$$

equation (5) can be converted to a form containing more familiar airplane parameters:

$$w = \frac{2W/S}{\pi^2 A\rho V}\,\frac{1}{r/b}\left\{1 - \exp\left[-\frac{(r/b)^2}{\left(42 + 4.8\,\frac{W/S}{\pi^2 A\rho V}\,t\right)\left(10^{-4}\right)}\right]\right\} \tag{7}$$

The vortex degeneration defined by equation (7), representing calm-air conditions and a span-load distribution of the generating airplane approximating an elliptic loading, can be considered a limiting condition - that is, the condition most conducive to persistence of the vortex intensity and severe effects on other aircraft penetrating the vortices. A wind of more than about 5 knots or convective action due to heating would be accompanied by atmospheric turbulence, particularly at the lower altitudes of terminal operations, which would tend to cause more rapid decay or complete disruption of the vortices. In the case where the vortices are close to the ground, frictional forces between the ground and the vortex-induced airflow would, presumably, contribute to the vortex decay. Another condition which apparently tends to produce less intense trailing vortices is a markedly irregular span-load distribution on the generating airplane, such as that associated with part-span flaps. Results presented in reference 3 indicate that the effects on an airplane encountering the vortices of another airplane with part-span flaps extended were much less severe, for the same separation time, than with the generating airplane in the no-flap condition. Available information on the effects of the foregoing alleviating conditions is not sufficient to permit quantitative consideration at this time. In examining the effects on airplanes encountering trailing vortices, in the next section, only the conditions of calm-air, elliptic load distribution and no ground frictional effects, as represented by equation (7), are considered.

Typical Vortex-Velocity Distribution

As an example of the vortex-velocity distribution and its attenuation with time, as defined by equation (7), the calculated induced vertical velocities along a line extending through and normal to both vortex center lines are shown in figure 3 for the case of a heavy jet transport flying at a speed approximating take-off climb or landing-approach speeds. The vertical velocities shown include the contributions of both vortices. The velocity distributions are shown for times after generation, or separation times, ranging from 1/2 to 3 minutes. It should be noted that pilots have reported apparent encounters with trailing vortices at separation times estimated at 5 minutes or more. However, actual measurements of vortex intensities have not been recorded for separation times greater than 160 seconds. (See ref. 3.) The results in reference 3 suggest that at some point in the orderly attenuation of the vortices, as represented in figure 3, they become unstable and deteriorate very rapidly. The factors which determine the time of this final dissipation of the vortices however are not known.

EFFECTS ON AIRPLANES PENETRATING TRAILING VORTICES

As illustrated in figure 1, there are three modes of penetration of the trailing vortices which will have distinctly different effects on the penetrating airplane. In each of these cases, only the most severe conditions, consisting of penetrations at the level of the vortex centers, will be considered in detail.

Cross-Track Penetration

The type of vortex encounter in which the penetrating airplane is crossing at right angles to the vortices tends to cause pitching and vertical motions and produce vertical loads on the airplane in a fashion similar to that of a gust encounter. This mode of penetration would be most likely to occur where airplanes are following different traffic patterns in the vicinity of an airport.

The vertical loads developed on three airplanes - a heavy transport, a light transport, and a light personal airplane - in crossing the wake of a heavy transport were computed and are shown in figure 4. The time of penetration in each case was taken as 1/2 minute after passage of the generating airplane and the vortex-velocity distribution shown in figure 3 for this separation time was used. The computations accounted for the rigid-body pitching and vertical responses of the affected airplanes and unsteady lift effects in a procedure similar to that described in reference 5. It was assumed that the pilots made no attempt to correct for the disturbances. The results are shown as plots of the ratio of total vertical load F to weight W (load factor) as a function of distance traveled across the wake. The light personal airplane, which was assumed to have a speed of 100 knots during the penetration, is shown to be subjected to positive and negative load factors of 3.2 and -1.2, respectively, closely approaching the design limit load factor in both directions. As indicated in reference 5, an instinctive control reaction by the pilot to the disturbances could cause a substantial increase in the loads to the extent that even the ultimate load could be exceeded, particularly in the negative direction, with structural failure of the airplane resulting. With separation times of more than a minute, loads would be substantially less than those shown, to the extent that there would be little danger of structural damage.

For the light transport, assumed to be traveling at 150 knots, the loads caused by the vortices are only a relatively small fraction of design limits and, except for the possibility of some passenger discomfort from the associated accelerations, should not cause a serious problem.

For the heavy transport with an assumed speed of 225 knots, the vortex loads are even smaller and again should not be of much consequence.

It should be noted also, that for the two larger airplanes with their slower response to controls and shorter time of disturbance, any reasonable control action on the part of the pilot, in contrast to the case of the light airplane, would not substantially increase the loads.

Along-Track Penetration Between Vortices

In the second type of vortex encounter considered, the penetrating airplane flying in a direction parallel to the vortices enters the vortex field midway between the vortex center lines. This is one situation which can occur in the take-off climbout or landing approach. As can be seen from figure 3, a primarily downward flow would act on the airplane and cause it to settle or at least reduce its rate of climb. Computations were made of this effect for several combinations of the three airplanes in the generating and penetrating positions and for a range of separation times from 1/2 to 3 minutes. The computations consisted in determining an effective induced-drag increment due to the downwash field of the vortices, as defined by equation (7), using simple strip theory and assuming an elliptical span-load distribution on the penetrating airplane. From this result, the decrement in rate of climb or, conversely, the increase in rate of descent, if the airplane is descending, was determined.

The results of the computations are shown in figure 5 as plots of decrement in rate of climb as a function of separation time. The curves on the left illustrate the effects on the light personal airplane penetrating the wakes of the heavy and light transports. The decrement in rate of climb due to the vortices of the heavy transport greatly exceeds the climbing capability of the small airplane and would cause a rapid settling of the airplane either in take-off climb or landing approach. Although the effect would diminish quite rapidly as the airplane is forced below the plane of the vortices, it could, nevertheless, cause the airplane to strike the ground, if at a relatively low altitude, before recovery could be effected. Of even greater hazard is the possibility of the pilot stalling the airplane in an effort to check the settling tendency. The settling effect due to the vortices of the light transport is much less than that of the heavy transport but still exceeds the climb capability of the small airplane and could be dangerous at low altitudes.

The curves on the right-hand side of figure 5 deal with penetration of vortex downwash fields by transport airplanes. With the vortices generated by the heavy transport, both the light and heavy transports would suffer large reductions in rate of climb even at the longer separation times. The available rate of climb is sufficient to more than offset these reductions, except at separation times of less than about 1 minute with the light transport. However, unless the penetrating airplane can pass through the vortex wake to a point substantially above it, the airplane could be forced to climb out at a greatly reduced climb rate in take-off or the pilot would have to apply a large amount of power to maintain planned glide slope in landing. Either of these situations would be hazardous near the ground.

In the case of the light transport following another light transport, the settling effect is much less than in the wake of a heavy transport and would not be as likely to cause serious difficulty.

As was pointed out earlier, when the centers of the trailing vortices settle to a height above the ground within about one span of the generating airplane, the vortices spread apart at a fairly rapid rate (about 700 feet per minute for the heavy transport and about 300 feet per minute for the light transport) and, as a result, the downwash field decreases rapidly. For example, with the vortex centers at a height of one-half span of the generating airplane the effects on following airplanes would be no more than 1/4 of those shown in figure 5 and would rapidly become less as the vortices spread further.

Along-Track Penetration Through Vortex Center

The third mode of encounter, and perhaps the most dangerous, consists in the airplane penetrating the center of one of the vortex cores on a path approximately paralleling the core. This type of encounter could occur during take-off climbout or landing approach. In this case, as can be seen from figure 3, the airplane would be subjected to vertical airflow having a downward direction on one wing and upward on the other; thereby a rolling motion of the airplane is induced.

Maximum rolling velocities were computed for this condition for the same airplane combinations and separation times considered in the preceding section.

The rolling velocities were determined by calculating, with simple strip theory, the rolling moment produced by the time-dependent, vortex-induced, normal-velocity distribution, defined earlier, and that resulting from rolling motion of the airplane, and equating these 2 moments.

The calculated rates of roll are shown in figure 6(a) as a function of separation time for all three airplanes penetrating the trailing vortex of a heavy transport and in figure 6(b) for the light personal and light transport airplanes penetrating the vortex of a light transport. The approximate maximum rates of roll that the airplanes could be expected to develop by full-deflection lateral control, at speeds typical of take-off climb or landing-approach conditions, are indicated by short coded lines at the left of the figures. It might be noted that, whereas the vortex-induced roll rate is essentially independent of speed of the penetrating airplane, the rate of roll available from the airplane's lateral controls is proportional to speed.

As shown in figure 6(a) the light personal airplane, caught in one of the vortices of the heavy transport, would roll very rapidly at the shorter separation times, the rolling being much more than the available control could produce and therefore more than it could counteract. The rolling action of the vortex decreases quite rapidly with separation time. At about 1.6 minutes, the controls would be capable of stopping the rolling motion. The vortex-induced roll rates of the transport airplanes are much less than those for the light airplane, particularly at the shorter separation times; however, the rolling capability of the controls is also much less, to the extent that the rolling of the transports could not be completely stopped by the lateral controls within the range of separation times shown.

With the vortices generated by the light transport (fig. 6(b)), rolling velocities of the light personal airplane are found to be higher than in the heavy transport vortex, except at the shorter separation times, and remain above the available lateral control roll rates throughout the range of separation times considered. On the other hand, the light transport in the vortex of another light transport would roll at a substantially slower rate than in the heavy transport vortex, the rate being of about the same magnitude as that available from the lateral control and showing little variation with separation time.

In order to provide a more direct indication of the lateral upset that might result from penetration of trailing vortices, computations were made of the bank angles reached, assuming the airplanes entered the vortex suddenly and remained at or near the center of the vortex for 2 seconds. It was also assumed that the pilot would quickly apply full lateral control against the rolling motion, the pilot's reaction time being taken as 0.3 second and the time to apply full lateral control thereafter as 0.3 second for the light airplane, 0.6 second for the light transport, and 1.0 second for the heavy transport. The rolling motion and the resulting angle of bank at the end of 2 seconds for the foregoing conditions were computed by well-known procedures by using vortex and roll-damping moments estimated by strip theory, and control moments appropriate to the type of airplane, as before.

The results of the computations of bank angle are given in figure 7(a) for the three airplanes penetrating a vortex of the heavy transport and in figure 7(b) for the light personal airplane and light transport in the vortex of a light transport. These results, also, are shown as a function of separation time. Except for the light airplane in the wake of the heavy transport at separation times of 2 minutes or more (fig. 7(a)), and possibly the light transport in the wake of another light transport (fig. 7(b)), substantial lateral upsets are indicated for all cases, which could be hazardous within, say, 300 feet of the ground in take-off or landing. Although the results indicate that the bank angle tends to be smaller for the larger and heavier airplanes affected, the extent of the upset that can be tolerated is also less because of slower and more difficult recovery.

It might be well to point out again that the foregoing estimates of the effects of vortex encounters are based on assumptions with respect to attenuation of the vortices which are somewhat speculative and only rather superficially supported by experimental results. Furthermore, there are a variety of conditions, such as atmospheric turbulence and effects of the ground surface and part-span flaps, which could cause more rapid weakening and disruption of the vortices and therefore less severe effects than those considered. In addition, the effects of vortex encounter would diminish markedly with increasing distance of the penetrating airplane above or below the plane of the vortex centers. For example, in the case of an airplane penetrating the vortex field of the heavy transport at 60 feet above or below the plane of the vortices, the disturbances to the penetrating airplane, even at very short separation times would be only one-half to two-thirds of those indicated for 3-minute separation time in figures 5, 6, and 7.

CIRCUMSTANCES OF VORTEX ENCOUNTER IN TERMINAL AREA

Having considered some of the possible consequences to aircraft encountering trailing vortices, this section deals with conditions under which such encounters might occur and some measures for avoidance of these encounters.

Near Perpendicular Encounter

As indicated earlier, the penetration of a vortex field at or near right angles to the vortex axes will generally occur when the two airplanes involved are in different phases of terminal area operations or are following different traffic patterns. In the first case, one airplane, on a crosswind leg of the traffic pattern or flying through the terminal area, may cross the track of another in take-off climbout, or landing approach. In the second case, the lightplane traffic pattern is frequently inside of and several hundred feet lower than the large-airplane pattern, so that the lightplane may well penetrate the wake of a large airplane during entry into the lightplane pattern. The conditions under which this type of encounter can be dangerous appear to be largely limited to the case of a light airplane crossing the wake of a large, heavy airplane within about a minute of the passage of the large airplane. As pointed out previously, this condition presents a strong possibility of structural damage to the small airplane. Such an encounter could always be avoided by any measures that would ensure that the altitude of the small airplane at the point at which it crosses the track of the large airplane is at least as great as that of the large airplane at the same point and has as great a separation time as possible after the large airplane passes. Because of the characteristic downward drift or settling of the vortex field, this procedure would provide a substantial clearance between the light airplane and the vortices - for example, the vortices of the heavy transport, considered herein, would have settled about 350 feet below the airplane's track a minute after it passed.

Take-Off and Landing Encounters

The possibilities of vortex encounters with serious consequences are probably greatest in the landing and take-off phases of operations. Here, successive departing or arriving aircraft are constrained to flight paths in essentially the same vertical plane, and disturbances to the airplanes would be more hazardous because of nearness to the ground. The primary effects of encountering a vortex field in these operations, where the airplane's track is roughly parallel to the axes of the vortices of the preceding airplane, would be a settling tendency, a rolling upset, or a combination of these effects, as already discussed in another section.

Take-off.- To aid in illustrating some of the possibilities of vortex encounter or avoidance in take-off, the estimated take-off climb path of the heavy transport is shown in figure 8(a) together with the vertical positions of its vortices at stated time intervals after passage of the airplane. Figure 8(b) shows the ground-induced lateral displacement of one of the vortices relative to the horizontal track of the airplane (center line) for the same take-off as in figure 8(a). With no wind, as assumed, the other vortex would be, of course, symmetrically disposed on the opposite side of the track. The spreading of the vortices would clear them from the path of a succeeding airplane at heights of 1/2 span or less of the generating airplane.

The effect of wind on the vortex disposition can be seen by displacing the vortex curves of figure 8 downwind a distance equal to the product of the wind speed by the separation times. For example, with a 5-knot headwind, the 1-minute curves of figures 8(a) and 8(b) would be moved about 500 feet toward the lift-off point; with a 5-knot crosswind the 1-minute curve of figure 8(b) would be moved 500 feet toward and across the airplane's track from the position shown. It should be noted that if the crosswind speed is equal and opposite to the lateral spread rate of one of the vortices, this vortex can maintain a fixed position above the runway at one point until the vortex dissipates. For the conditions of figure 8(b), a 5-knot crosswind would result in a relatively stationary vortex lying across the runway about 1,200 feet from the lift-off point at a height of about 50 feet and at an angle from the runway direction of about 30°. Thus it appears that light crosswind components tend to increase the probability of encountering vortices close to the ground (heights up to about 1/2 span of the generating airplane) and to decrease the probability at greater heights.

Consider, now, several cases of successive take-offs by various combinations of the three airplane types. The lightplane taking off after the heavily loaded heavy transport, represented in figure 8, would be capable of lifting off 5,000 to 6,000 feet earlier than the large airplane and climbing out at about the same climb angle. It should therefore be able to stay well above the path of the large airplane with no possibility of vortex encounter, regardless of separation time. Similarly, the light transport, with a shorter take-off roll and probably a greater climb gradient than a preceding heavily loaded heavy transport, would not be subject to vortex encounter. In other words, if the second airplane of a pair in successive take-offs can leave the ground about 1,000 feet short of the lift-off point of the first airplane (to allow for light headwind drift of the vortices) and is capable of at least as steep a climb angle, there would be little or no possibility of encountering the vortices of the preceding airplane, and the time interval between take-offs would not be determined by vortex considerations.

In the cases of airplanes of the same or similar type taking off in succession, there is a real possibility of dangerous vortex encounter. Using the heavy transport as an example, two such airplanes, although similarly loaded and basically capable of equal performance, would, in practice, lift off at somewhat different distances down the runway and follow somewhat different climbout paths because of normal piloting variations. If 1,000-foot variation in take-off point and 1° variation in climb angle (referring to fig. 8(a)) are assumed, it can be seen that, with a separation time of 1/2 minute, the second airplane could pass through the height level of the vortices of the first airplane at a height of about 60 feet and again at about 200 feet. Penetration of the vortices at either point could be dangerous. With a separation time of 1 minute, the second airplane could again cross the height level of the vortices at 60 feet and cross a second time at a height of about 1,000 feet. At the latter height, the hazard of a vortex encounter would be less and, since normal lateral deviations in the track of the airplane relative to that of the preceding airplane tend to increase with distance from the lift-off point, the probability of vortex encounter would be less. In this case, then, with no crosswind component, a separation time of 1 minute between take-offs might be adequate. With a light crosswind, however, a vortex could lie in the path of the second airplane at the 60-foot level for whatever length of time might be required for the vortices to dissipate. A separation time of 2 to 3 minutes between take-offs might be required in this case.

As another example, two aircraft of the same type such as the heavy transport can have substantially different take-off weights, which would have large effects on take-off performance but relatively little effect on the intensity and drift characteristics of their trailing vortices. The more lightly loaded airplane taking off after the heavier one should have no vortex problem; however, for the reverse sequence, there would be a possibility of vortex encounter which should be considered in setting the take-off interval.

There are many more possible combinations of airplanes in successive take-offs which cannot be considered in detail, and no general rules can be stated for separation requirements to avoid vortex encounters. In general, if the possibility of vortex encounter is to be considered in determining separation of aircraft in take-off, suitable sequencing of aircraft to take account of differences in performance and differences in size and weight could reduce the average separation time and increase the traffic flow rate. Any optional procedures, such as starting the take-off roll from a runway intersection rather than the end of the runway, should be avoided if they result in the airplane leaving the ground beyond the lift-off point of a preceding airplane of equal or greater size and weight.

Landing.- The positions of the vortices of the heavy transport relative to its landing approach path at several times after passage of the airplane are shown in figure 9. The glide slope of the airplane was taken as 3°. (Note change in horizontal scale from fig. 8.) Since the weight of the airplane was assumed the same as for the take-off of figure 8, the vertical and lateral drift of the vortices are also the same. Wind effects on the vortex positions would be similar to those discussed for the take-off, except that, for landing a headwind would move the vortices away from the path of a following airplane rather than toward it, as in the take-off case.

It is apparent that with no crosswind, another airplane following exactly the same landing path as a preceding heavy transport would not be seriously affected by its vortices with an interval as little as 1/2 minute. In poor visibility conditions, with airplanes in the landing approach guided by the instrument landing system (ILS), they are constrained to follow within about $\pm 1/2^{\circ}$ of the same glide slope. For example, for the glide slope illustrated in figure 9(a) all aircraft on ILS should be within ±75 feet of the nominal flight path at a height of 300 feet. The vortices of the heavy transport descend or, near the ground, move laterally at a rate of 300 to 350 feet per minute, so that with 3/4- to 1-minute separation there should be adequate clearance between the vortices and the following airplane, at least for no-crosswind conditions. The vortices of a light transport would descend and spread more slowly than those of a heavy transport - about 150 feet per minute. The separation time for a smaller following airplane, therefore, should probably be about $1\frac{1}{2}$ minutes for the condition just cited. With a light crosswind, as in the case of take-off, the vortices near the ground can be blown back across the runway, so that separation times, in some instances, would have to be increased over the values quoted above. This added delay could possibly be avoided if a procedure could be followed whereby the following airplane, particularly if smaller than the preceding one, would follow a flatter path after "breakout" than the ILS glide slope and land further down the runway.

Under visual flight rules (VFR) conditions, there will generally be much more variation in landing approach paths, particularly among different classes of airplane where the smaller, lighter aircraft tend to follow steeper approach paths. In this case, it seems that separation times, from vortex considerations, could be reduced relative to those for ILS conditions by taking advantage of the varying approach-path capabilities of different classes of airplane. For example, if by some visual glide-path aid, a number of which have been proposed, the approach paths could be controlled so that the smaller aircraft types would approach more steeply and touch down further down the runway than the larger ones, and if traffic could be suitably sequenced so that the landings of similar larger aircraft following the same glide slope would be interspersed with the lighter aircraft landings, then separation times as short as 1/2 minute could be acceptable.

Missed approach.- Occasions frequently occur where aircraft pull up from landing approaches and climb back to traffic pattern altitude. Should a light personal airplane or a light transport be following a light or heavy transport that executes a "go-around" and less than a 2- or 3-minute separation interval exists, it should also pull up and climb back to traffic pattern altitude as rapidly as possible. Otherwise, there is a very strong possibility that the following aircraft will encounter the wake of the first airplane, since it may either descend through the wake level in the air or encounter it lying over the runway should a light crosswind exist.

Also, take-offs should be delayed for 2 to 3 minutes after an aircraft which is pulling up has passed over the aircraft in take-off position. In this case, also, a light crosswind would help clear the climb path but may well hold vortices that reach ground level in a dangerous position with respect to the runway.

Use of parallel runway.- The horizontal motion of the vortices of a heavily loaded large transport near the ground during take-off or landing combined with the drift due to a light crosswind of, say, 3 to 5 miles per hour, could cause the vortices to reach a parallel runway 1,000 feet away with dangerous strength remaining. However, if one runway handled only take-offs and the other only landings, this hazard could be reduced to negligible proportions with the 1,000-foot spacing, except that the go-around case could still cause difficulty if a light crosswind exists. In the latter case the vortices could interfere with the traffic on the other runway. If each runway of a parallel system is expected to handle both take-off and landing traffic, then the spacing must be about 2,500 feet to assure freedom from vortex interference.

CONCLUDING REMARKS

By way of conclusion, some general remarks relating to the vortex problem might be appropriate.

Although vortex encounter can be a real hazard, such an encounter requires that an airplane be in a certain limited spatial region at a certain time and under suitable atmospheric conditions. Such a combination of circumstances apparently occurs rather infrequently, as attested by the still relatively few serious incidents attributed to vortices despite the frequent high-density traffic in some terminal areas.

The exposure to the vortex hazard, particularly in the sensitive take-off and landing operations, can be substantially reduced by suitable air-traffic control procedures which emphasize appropriate sequencing and spacing of traffic and control of flight paths.

Education of aircraft users as to the potential hazard and behavior of the invisible but powerful trailing vortices could be a significant factor in avoiding this hazard.

Analytical studies, beyond the scope of this paper, would be required to determine the extent to which operations planning and traffic control should be tailored to achieve an acceptable level of risk of exposure to the vortex hazard, and the effects of these modifications on traffic flow rates.

Further research, dealing with the trailing-vortex problem should be directed primarily to determining the persistence of vortices near the ground as affected by airplane characteristics and atmospheric conditions.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., January 28, 1963.

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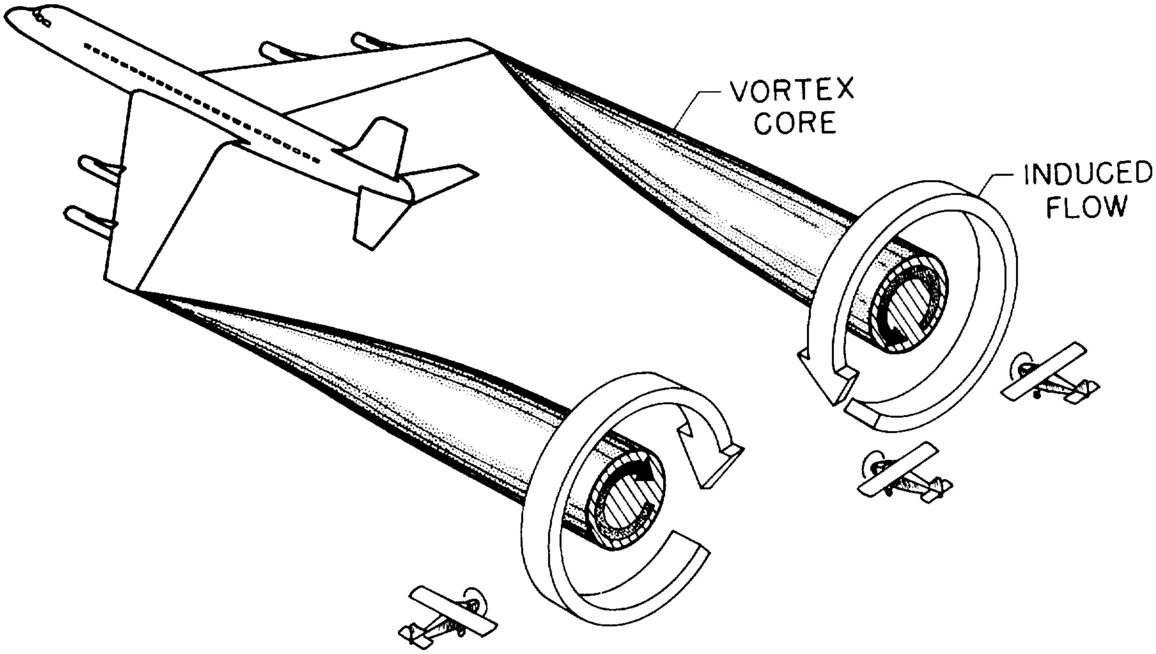


Figure 1.- Illustration of trailing vortex wake and types of encounter.

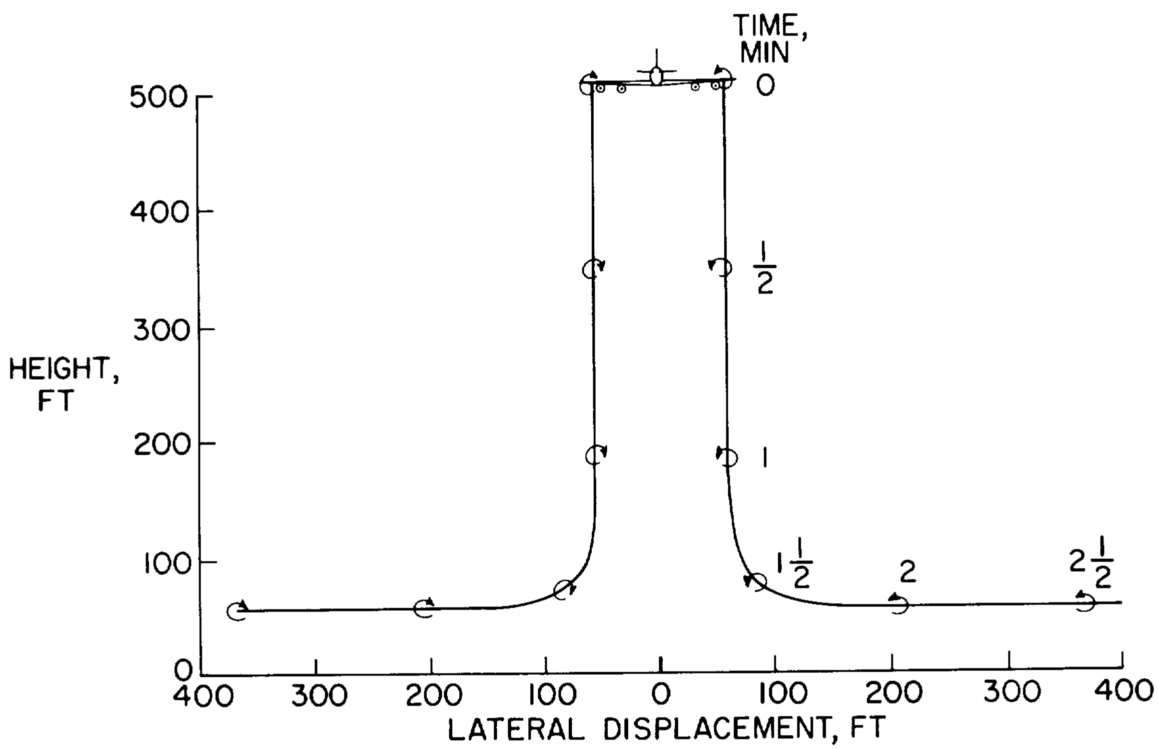


Figure 2.- Vertical and lateral displacement of vortex pair due to mutual and ground interactions. Calculated for heavy transport at 160 knots.

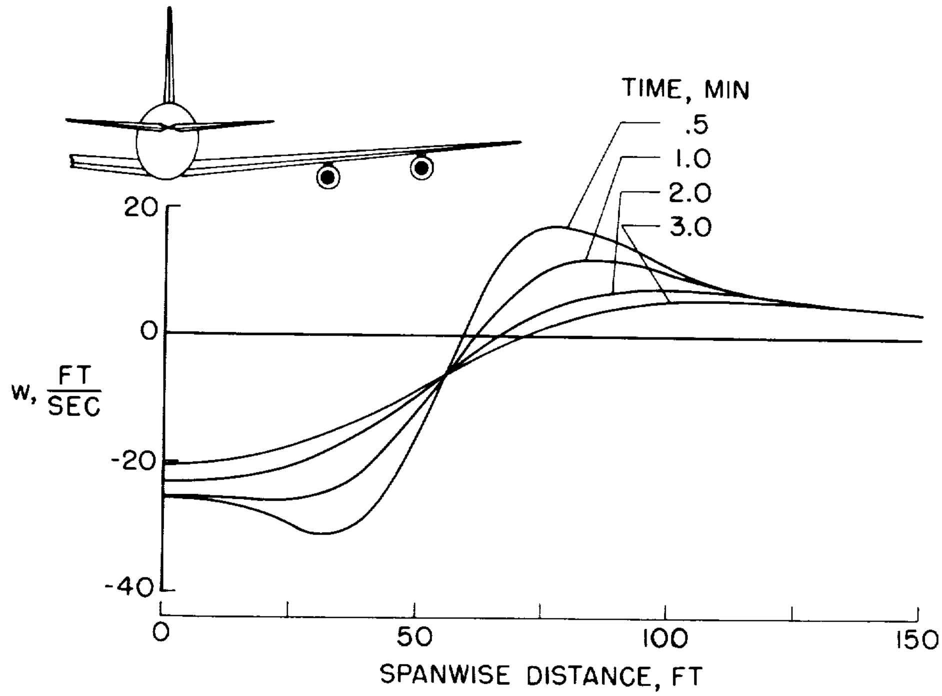


Figure 3.- Spanwise variation of vortex-induced vertical velocity, illustrating attenuation with time in calm air. Calculated for heavy transport at 160 knots.

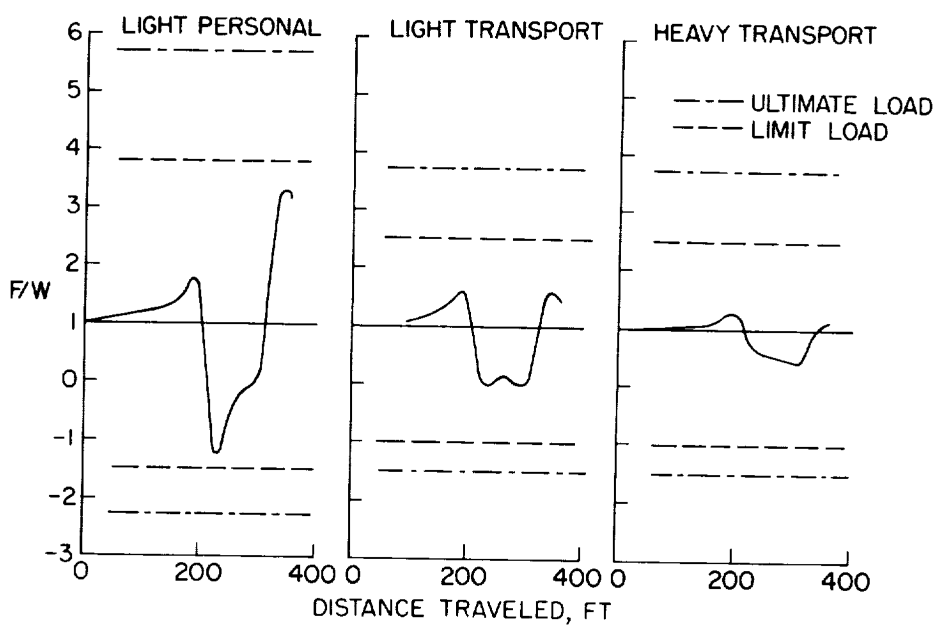
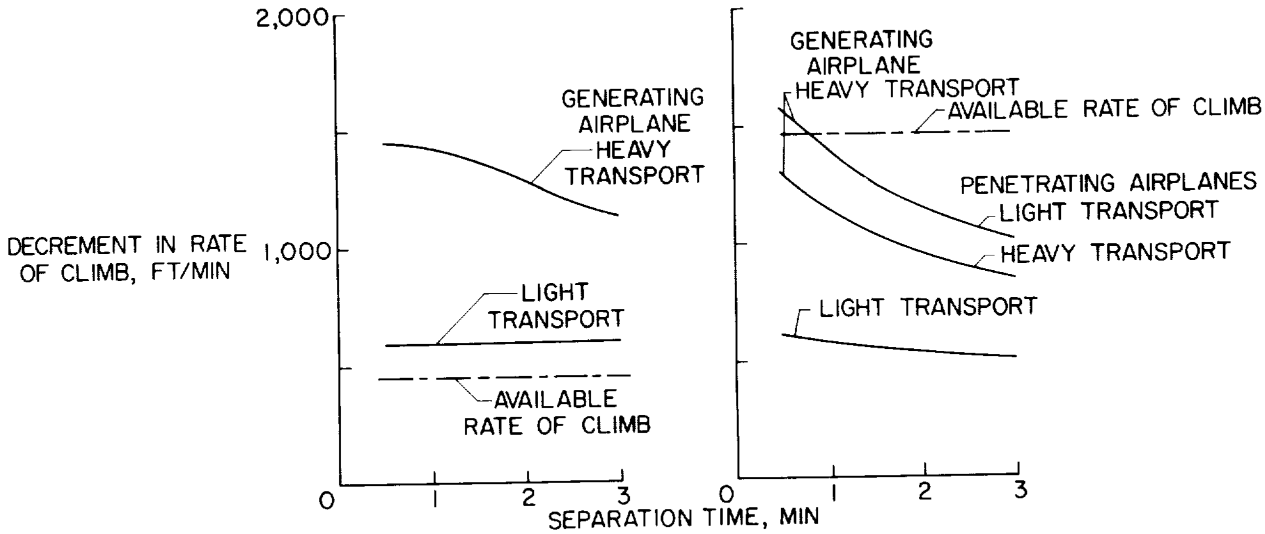


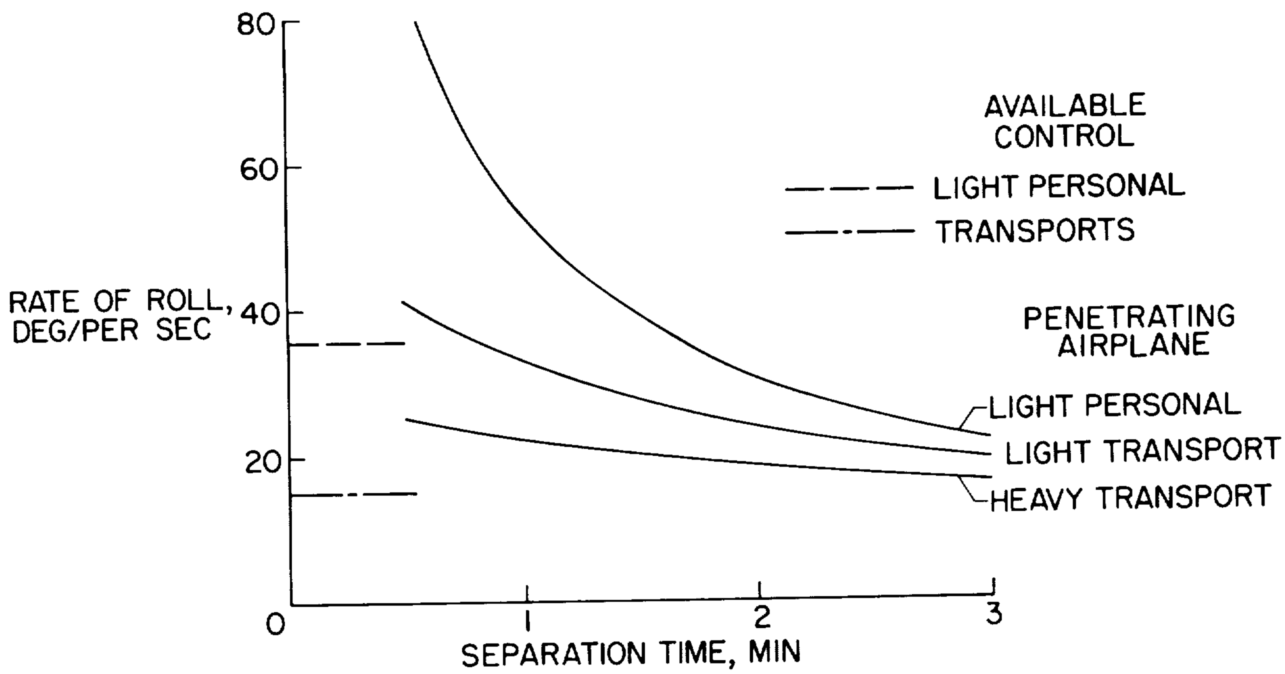
Figure 4.- Vertical loads imposed on three airplanes crossing the vortex wake of a heavy transport. Calculated for time interval of 1/2 minute. Design limit and ultimate loads shown for comparison.



(a) Penetrating airplanes; light personal.

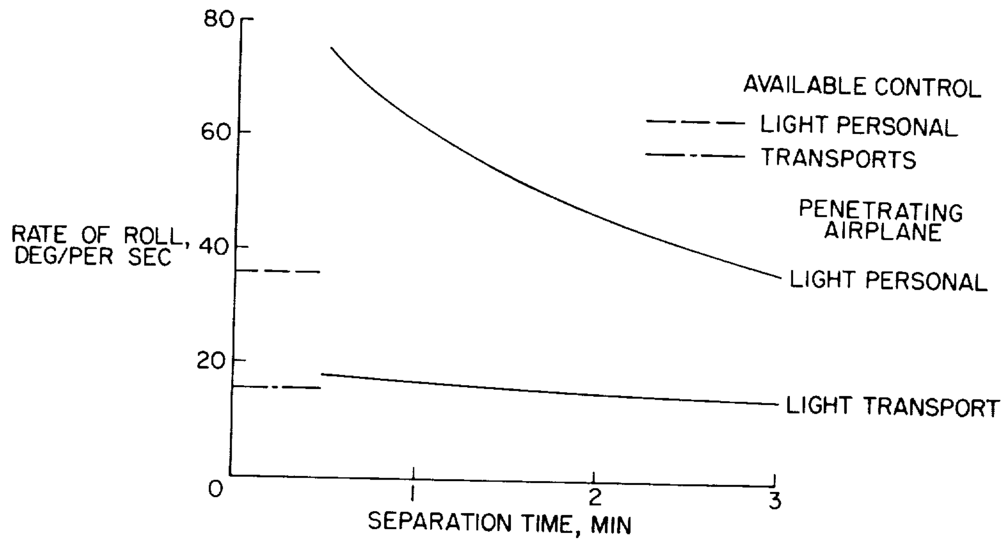
(b) Penetrating airplanes; transports.

Figure 5.- Decrement in rate of climb (settling effect) resulting from penetration midway between and parallel to vortices. Calculations shown for various combinations of generating and penetrating airplanes.



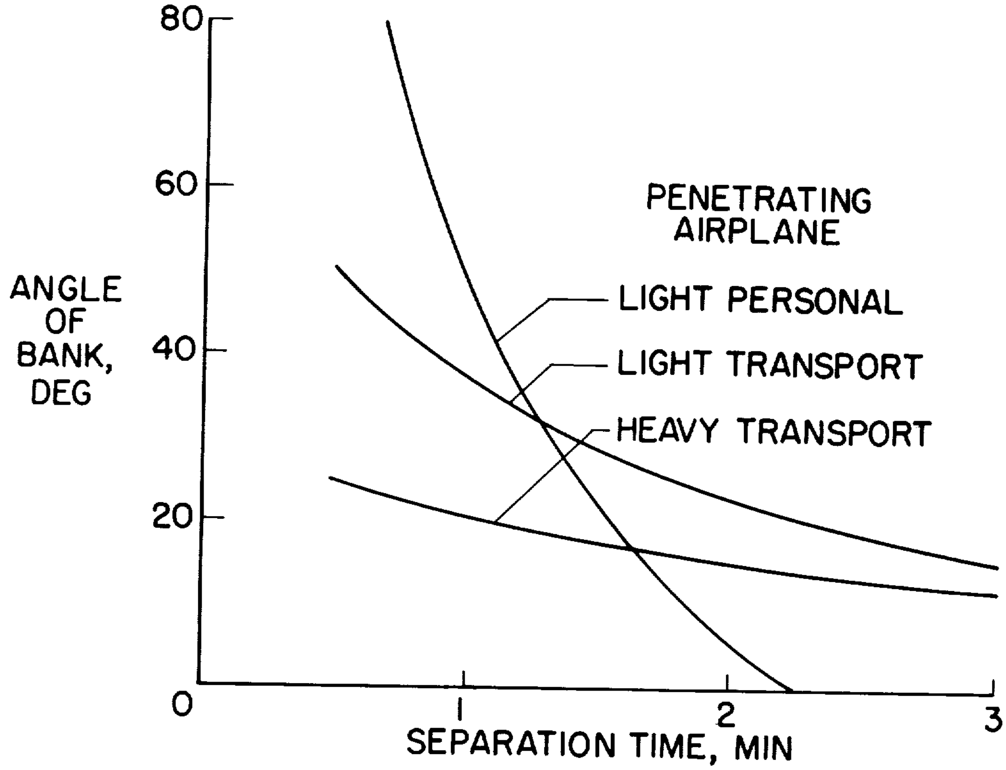
(a) Vortex generated by heavy transport.

Figure 6.- Calculated maximum rate of roll due to penetration along core of vortex.



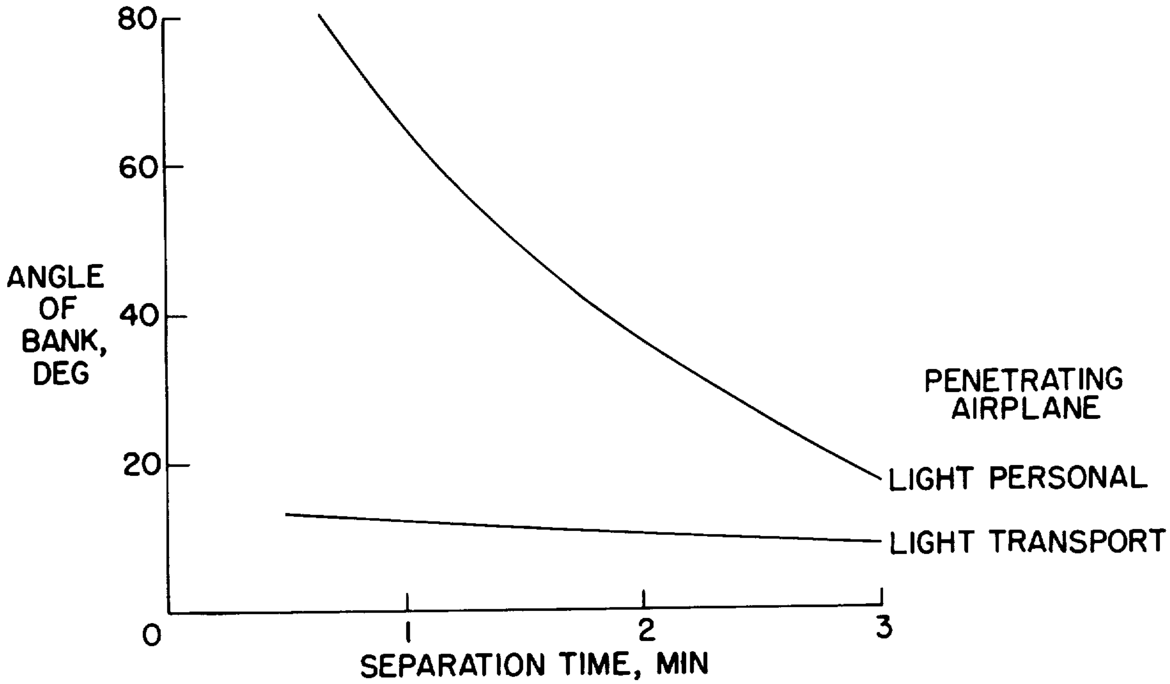
(b) Vortex generated by light transport.

Figure 6.- Concluded.



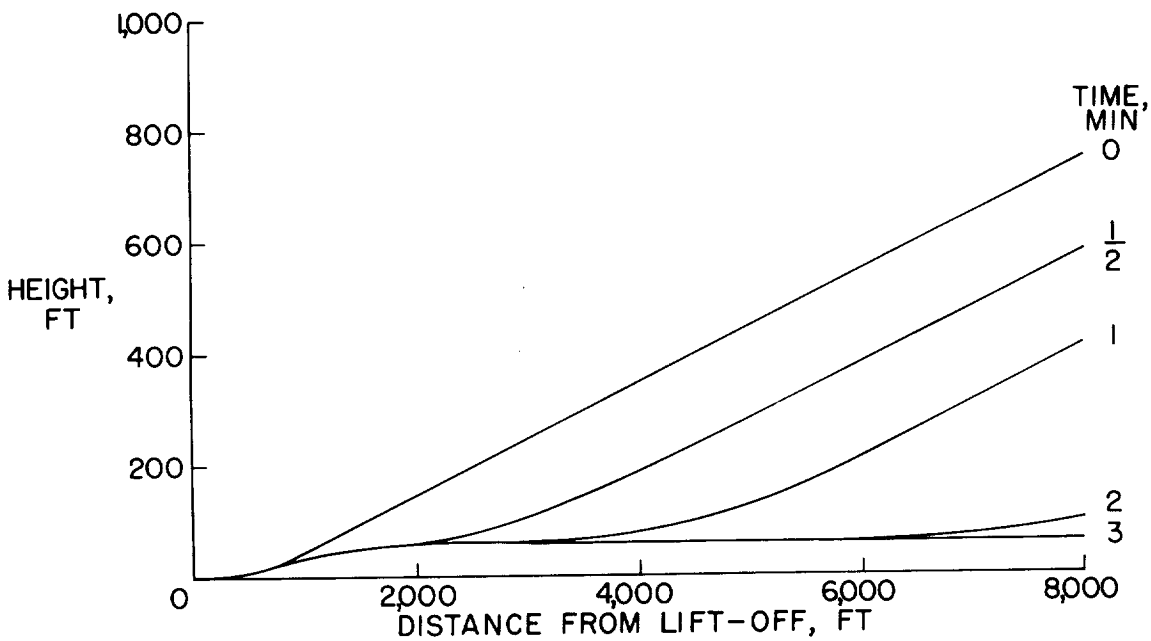
(a) Vortex generated by heavy transport.

Figure 7.- Calculated angle of bank produced by penetration along core of vortex. Full corrective control and time in vortex of 2 seconds assumed.



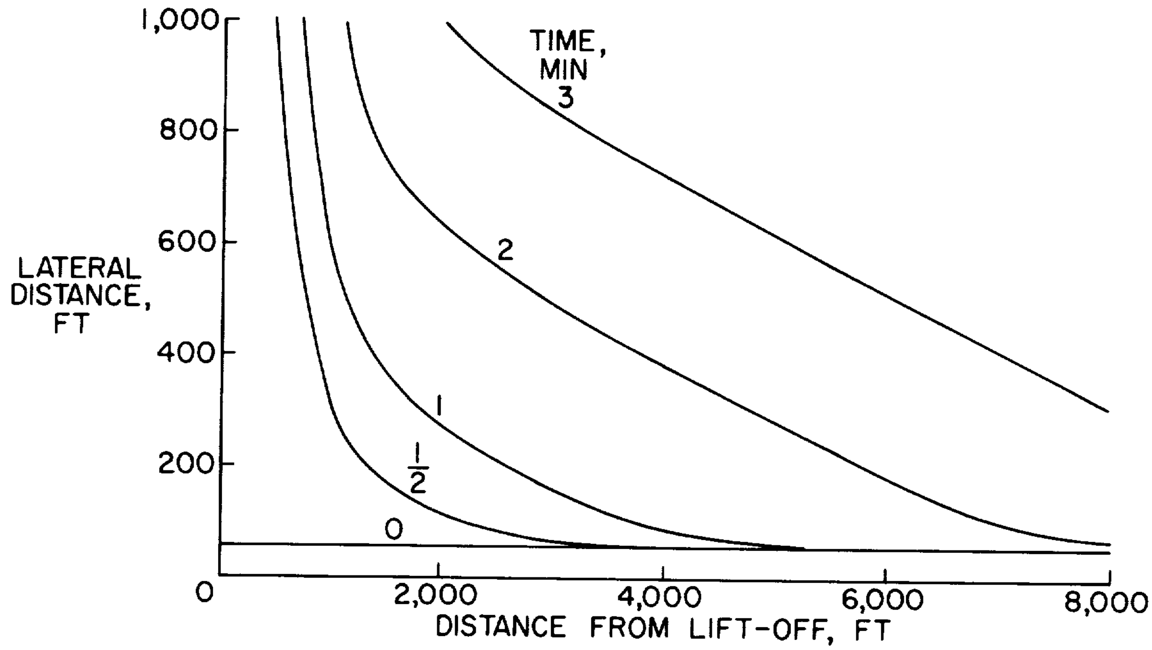
(b) Vortex generated by light transport.

Figure 7.- Concluded.



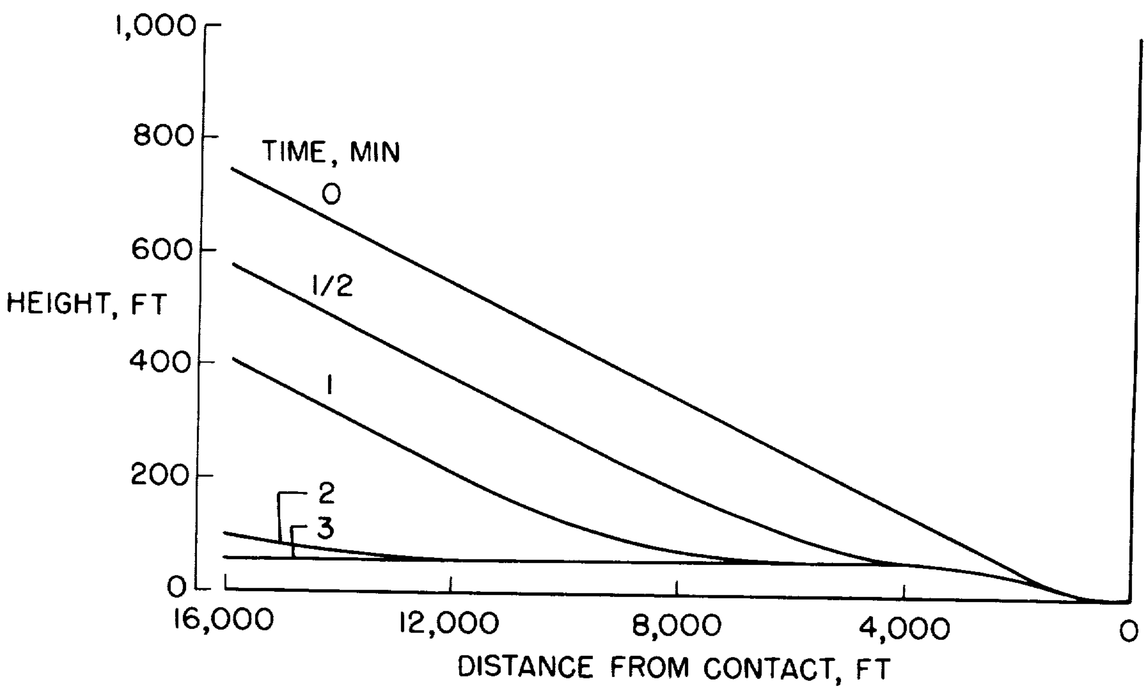
(a) Vertical positions of vortices.

Figure 8.- Vortex positions calculated at several times relative to take-off flight path. Heavy transport; no wind.



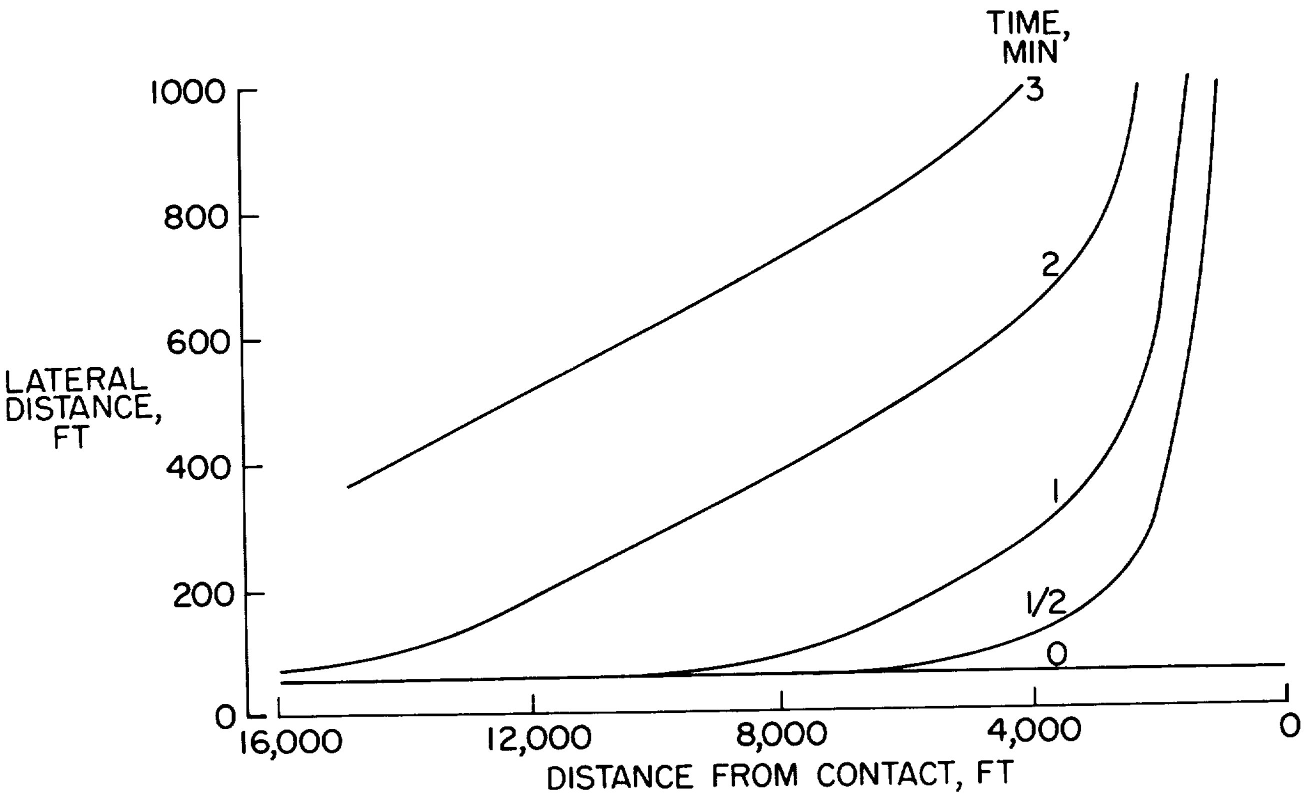
(b) Lateral positions of vortex.

Figure 8.- Concluded.



(a) Vertical positions of vortices.

Figure 9.- Vortex positions calculated at several times relative to landing flight path. Heavy transport; no wind.



(b) Lateral positions of vortex.

Figure 9.- Concluded.